Identifying farm-type specific entry points for innovations in weed management in smallholder inland-valley rice-based systems in West Africa

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ABSTRACT

In West Africa, weeds are major production constraints in rain-fed lowland rice systems — often located in the inland valleys. Weed management technologies have been developed and promoted in such rice systems, but adoption by farmers lags behind, probably because of insufficient considerations of the system diversity or the farm-specific characteristics during technology development or promotion. This study aimed to identify farm-type specific entry points for innovations in weed management practices of smallholders in rice-based systems in inland valleys. We conducted farm surveys in the Mono Couffo region of Benin in 66 fields in 2010 and 2011 in a range of socio-economic settings typical for smallholder farms. A combination of multivariate analyses using Principal Component Analysis and Agglomerative Hierarchical Cluster is helpful in constructing farm typologies. This categorization, in turn, enables the assessment of farm-type specific weed management strategies and consequently the identification of entry points for innovation. Specific entry points for innovations in weed management include: (i) complementing the existing range of curative options by more preventive measures, (ii) diversifying the existing range of curative measures (mainly hand weeding and herbicide application) by measures that are both non-chemical and labor-saving, and (iii) improving women farmers' access to information and inputs by targeted training endeavors and conducive credit systems.

Keywords: farm typology; rain-fed lowland rice; vegetables; Benin

1. Introduction

West Africa is characterized by an increasing pressure on land resources due to a rapidly growing population. In some regions, arable land in the uplands has become scarce due to soil degradation and severe weed infestation, following a shortening of the fallow period traditionally used to avoid such problems (Giertz et al. 2012). Consequently, expansion of arable land into alternative cultivation areas is observed. Inland valleys — seasonally flooded lowlands with a generally higher water availability, and soil fertility compared to uplands — are attractive alternative cropping environments (Giertz et al. 2012; Rodenburg et al. 2014). Indeed, intensification and diversification practices are frequently observed in the inland valleys in West Africa. While rice (*Oryza sativa* L.) is the only staple crop that can be grown in the seasonally submerged valley bottom lands, other crops (mainly vegetables), aquaculture and livestock can be important components of the farming systems that interact both with rice production and non-agricultural

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land uses in inland valleys across space and time (Erenstein et al. 2006). In inland valleys, rice and indigenous vegetables are the first and second most important food crops, respectively. These crops are grown either in rotations or as sole crops. Rice is grown during the wet season (May to November) and vegetables are grown on residual soil moisture in the dry season (December to April). Most inland valleys have an undulating topography and a high spatial variability in soil fertility, hydrology, and weed infestation (Windmeijer et al. 2002). In inland valleys, the lack of a permanent and adjustable water layer may favor weed infestation, leading to severe crop–weed competition with yield losses in the range of 28–89% in the absence of weed control and averaging 23% despite control (Rodenburg and Johnson 2009). Indeed, competition from weeds is the most important overarching physical production constraint in inland valleys of Africa (Rodenburg et al. 2014). Weed-inflicted yield losses in rice in smallholder farming systems, prevailing in this region and production environments, are high because weed management efficacy is often suboptimal. This in turn is partly due to a low adoption rate of effective (improved) weed management technologies. The single most important weed control intervention practiced in small-scale rice production systems in Africa is hand weeding (Rodenburg et al. 2019). Because of the high labor requirement for this practice, and the short supply of this in farming households due to competing claims imposed by other farm activities, weeding is often inadequate or late (Rodenburg and Johnson 2009; Ogwuike et al. 2014).

The low adoption of improved weed management technologies partly reflects the general mismatch between the currently available weed technologies and the socio-economic and institutional conditions of smallholder farmers in Africa (e.g., Johansen et al. 2012; Schut et al. 2015). Agricultural technology development and dissemination efforts often assume homogeneity of the farming population with respect to socio-economic variables (Somda et al. 2005). Adoption of technologies, however, varies among smallholder farm households just because of differences in such socio-economic characteristics (e.g., Somda et al. 2005; Huat et al. 2013). To improve overall weed management efficacy in smallholder rice farming systems, innovations in weed management need to be developed or identified, which better match the context this type of farmers are working in. While this has been suggested before (Rodenburg et al. 2015; Jordan et al. 2016), to our knowledge such approach has never been operationalized before; hence, the novelty of the current study.

Identifying farm-type specific entry points for innovations in farmers' weed management practices is an important challenge. Farmers' surveys are of great importance for setting the research agenda, testing research hypotheses, designing extension strategies, evaluating the effectiveness of projects and development interventions (Khan and Damalas 2015). To this end, farmers' surveys were carried out in inland valleys in the Mono Couffo region of Benin. In this context, the aim of this study was to identify entry points for intervention in the development of farmers' weed management practices to improve rice-vegetable productivity in the area. This has been achieved by: (i) distinguishing farm types that might be expected to exhibit different behaviour concerning to the adoption of technology and (ii) examining farmers' current cultivation and weed management practices in inland-valley rice-based systems.

2. Materials and methods

2.1. Study sites

The study was conducted during the 2010 and 2011 cropping seasons in three valleys, near the villages Agbedranfo, Vovokame, and Houinga, in the departments of Mono (1860 km^2) and

Couffo (2250 km^2) in South-West Benin, West Africa. These sites are located in southern Guinea Savanna zone of West Africa, characterized by a bi-modal rainfall regime and are representative for lowland rice-based production systems in West Africa (Windmeijer and Andriesse 1993). Site selection was aimed at obtaining a broad range of representative inland valleys, covering the prevailing situations with respect to crop and water management. A detailed characterization of the study sites is presented in **Table 1**.

Table 1. Selected characteristics of the villages of Agbedranfo, Vovokame and Houinga under study.

DEPARTMENT	Couffo	Couffo	Mono
MUNICIPALITY	Dogbo	Dogbo	Houeyogbé
VILLAGE/WATERSHED	Agbedranfo	Vovokame	Houinga
LOCATION			
Longitude (º)	1.72 E	1.75 E	1.82 E
Latitude (º)	6.76 N	6.79 N	6.59 N
CLIMATE			
Agro-ecological zone	Southern guinea savanna	Southern guinea savanna	Southern guinea savanna
Growing period (days)	225	225	240
Annual rainfall (mm)	950	950	1100
Rainfall distribution	Bimodal	Bimodal	Bimodal
PRODUCTION SYSTEM			
Tillage	Manual/tractor	Manual	Minimum tillage
Seeding methods for rice	Dibbling in lines	Dibbling in lines	Transplanting
Rice varieties	Improved	Improved	Improved
Seeding methods for vegetables	Broadcast/dibble/transplant	-	Broadcast/dibble/transplant
Vegetable varieties	Traditional	Traditional	Traditional
Intercrops	Okra/pepper	-	-
Rotation crops	Rice/vegetable	Rice/sweet maize	Rice/vegetable
Input use	Some NPK and urea	Some NPK and urea	Some NPK and urea
Irrigation	Artesian well	Artesian well	None
Production objective	Smallholder/sale	Smallholder/sale	Smallholder/sale
Aquaculture	Fish farming in ponds	-	-
Mechanism of intensification	Crops cycles,+/-mechanization	Crops cycle	Use of inputs (herbicides)
Access to market a	Moderate	Good	Moderate
Decision maker	Men/women	Men/women	Men/women
Land tenure	Inheritance, rented	Inheritance, purchased	Inheritance, purchased
REGIONAL IMPORTANCE			
Studied lowland area	40	12	200
Share of inland valley area (%) in the region	0.2	0.1	

[a] Market access is defined by distances from all-weather roads: good (< 2 km), moderate (< 5 km), bad (> 5 km).

2.2. Survey

The number of farms in each village was determined with the help of local farmers groups. A random sampling of 21 out of 121 (17%) farm heads from Agbedranfo, 22 out of 95 (23%) farm heads from Vovokame, and 23 out of 102 (23%) farm heads from Houinga were surveyed. A survey to classify farm types was conducted among 66 farmers cultivating rice in rotation with vegetables, and rice and vegetables in monocrop with no rotation (**Table 2**).

Table 2. Characteristics of cropping systems in three villages of the study area (South West Benin); values represent the number of farmers.

Cropping systems (n)	Villages			Aggregate villages
	Agbedranfo	Vovokame	Houinga	
Fallow-jute mallow (*Corchorus olitorius*)	3	-	3	6
Fallow-eggplant (*Solanum macrocarpum*)	-	5	2	7
Fallow- hot pepper (*Capsicum frutescens*)	-	4	2	6
Fallow-tomato (*Solanum lycopersicon*)	3	-	2	5
Fallow-okra (*Abelmoschus esculentus*) + hot pepper	3	-	-	3
Rice-jute mallow	9	-	-	9
Rice-eggplant	-	-	2	2
Rice-okra	3	-	-	3
Rice- sweet corn (*Zea mays*)	-	10	-	10
Rice-tomato	-	3	-	3
Rice monocrop	-	-	12	12
Total	21	22	23	66

The survey consisted of a semi- structured questionnaire that was administered on the farm, supplemented by a field visit. The questionnaire covered questions on (i) socio-economic and farming system attributes; e.g., household attributes, education level, contact with extension agents for training or counseling on good agronomic practices, off-farm activities, source of income, land tenure, use of farm and hired labor and market accessibility, and (ii) characteristics of the production system; e.g., farm size, land use, crop production, and input uses. A sub-sample of 45 farmers — including those who produced lowland rice in the wet season and vegetables in the dry season, or those who practiced rice monoculture — was selected in the three villages for detailed observations of the cropping practices. Among this sub-set of farmers, land preparation and weeding practices were recorded during the rainy season for lowland rice and during the dry season for vegetables.

For lowland rice only, labor input and crop yields were measured. The total time spent on the field for weeding was recorded for each farm, and the weeded area was measured. Time records were held daily and for all workers individually. Children under 13 years were accounted for as half an adult, while no distinctions were made between men and women workers. Rice grain yields were assessed using a weighing scale and were corrected to 14% moisture content using a grain moisture meter (Riceter m 401, Kett Electronic Laboratory, Tokyo, Japan).

2.3. Data analysis

Farm household data comprising farm family characteristics, farm employment, land tenure, farm size, labor availability, use of technological attributes (inputs and equipment), financial resources, and market access were analyzed, and farm typologies were constructed, using two methods of multivariate statistical analyses: the Principal Component Analysis (PCA) followed by an Agglomerative Hierarchical Cluster algorithm (AHC). PCA is used to reduce the number of variables, as it defines the underlying structure in a data matrix and analyzes the nature of the interrelationships among a typically large number of variables by defining a set of common underlying factors (Köbrich et al. 2003). According to Kaiser's criterion, factors presenting an eigenvalue greater than one were retained. Kaiser's criterion is appropriate when the number of variables is less than 30 (Field 2005; Bidogeza et al. 2009), which is the case for our data set with 20 variables. Then, factors retained in PCA were used in AHC. Cluster analysis is used to classify the observations according to m-variables (farm households) of an n-dimensional (farm household attributes) space (Köbrich et al. 2003). At each step, the algorithm classifies individuals into pairs by selecting the individuals with minimum dissimilarity (Blazy et al. 2009). The pairs of observations obtained through AHC are aggregated using Ward's minimum-variance method (Köbrich et al. 2003).

Survey data on weed management practices and rice crop yields were encoded and frequency tables were made using Excel (Microsoft 2013). Fischer tests (F) and Chi-square tests at $P \leq 0.05$ were conducted using SPSS version 16.0 (SPSS 2007). The LSD values were presented when there was a significant treatment effect ($P \leq 0.50$).

3. Results

3.1. Characteristics of the farm typology

The PCA allowed us to reduce the number of factors in the data by selecting the first ten factors with eigenvalues higher than 1 (**Table 3**). These ten factors explained 81% of the total variance. The first factor (F1), which explained the largest part of the variance (23%), was positively associated with gender, off-farm employment, land area in developed lowland, and sale of vegetables. However, it was negatively correlated with on-farm members, i.e., households headed by women facing labor shortage are most likely to engage in off-farm activities and sale of vegetables cultivated mainly on small farm sizes in the developed lowland. The second factor (17% of the variance) related to ownership and access to large undeveloped lowland with uses of inputs (herbicides and fertilizers) for rice production and returns in cash. This factor can be related to variables accounting for the level of intensification in rice production. The third factor (9% of the variance) was associated with a variable accounting for the diversification of activities in addition to agriculture for both men and women. The fourth factor (7% of the variance) was related to household members and on-farm family members. In other words, large households have more family labor input. Factor 5 (6% of the variance) was associated to household members and education level of farmers. This relationship implies that large households have more educated members. Each of the next four factors (6, 7, 8 and 9) explained about 4% of the variance and related to the variables presenting contact with agricultural extension services that contribute largely to the dissemination of improved technologies.

Table 3. Ten components resulting from principal component analysis with factor loadings for each of the twenty variables and percent cumulative variance explained.

Variables	Factor loadings									
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Farm family characteristics										
Gender	0.832*[a]	0.235	0.298	-0.187	-0.303	-0.029	-0.201	-0.119	0.097	-0.042
Age of the farmer	0.379	0.116	-0.055	0.261	-0.320	-0.311	0.265	-0.512*	0.011	0.082
Education level of farmer	0.272	0.382	0.223	0.316	0.543*	0.285	0.195	0.279	-0.035	-0.031
Contact with extension services	-0.097	-0.072	-0.034	-0.035	0.190	0.546*	0.519*	0.532*	0.573*	-0.198
Total household members	0.675*	0.247	0.126	0.573*	0.519*	0.183	-0.150	-0.088	-0.146	0.332
Off-farm employment										
Off-farm occupation	0.745*	-0.075	0.543*	-0.114	-0.095	0.162	-0.018	-0.539*	-0.185	-0.017

Land tenure										
Ownership	0.477	0.537*	-0.027	-0.041	-0.115	-0.023	-0.133	-0.039	0.567*	-0.153
Renting/borrowing	0.092	0.209	0.262	-0.103	0.158	0.270	0.593*	0.436	-0.132	0.600*
Farm size										
Developed lowland	0.813*	0.345	-0.001	0.078	-0.084	0.011	-0.116	0.122	-0.115	-0.166
Undeveloped lowland	-0.521*	0.755*	0.213	-0.068	-0.019	-0.063	0.151	-0.070	-0.005	-0.255
Labor availability										
On-farm members	-0.763*	-0.261	0.276	0.503*	-0.062	0.451	0.084	0.516*	0.097	-0.097
Technical nature of crop management										
Herbicides	0.111	0.638*	-0.195	0.151	0.071	0.112	-0.290	0.513*	0.305	0.026
Insecticides	0.575*	0.256	0.287	0.070	0.131	0.003	0.084	0.041	0.591*	-0.119
Fertilizers	0.170	0.631*	0.256	0.472	0.259	-0.184	0.181	-0.043	0.015	0.151
Irrigation equipment	-0.536*	0.450	0.255	-0.060	0.178	-0.154	0.194	0.167	0.632*	0.232
Rotation	-0.302	0.495	0.487	0.160	-0.233	-0.110	0.548*	0.052	0.170	-0.104
Capital										
Sale of rice	-0.108	0.624*	-0.122	0.147	-0.006	-0.200	-0.193	0.039	0.035	-0.522*
Sale of vegetables	0.752*	0.251	-0.153	-0.401	0.475	-0.105	-0.250	-0.052	0.511*	-0.228
Sale of fish	-0.105	-0.164	0.465	0.350	0.146	0.512*	0.029	0.051	-0.005	-0.069
Market access										
Distance to major urban areas	0.493	0.183	-0.008	0.267	-0.213	0.260	-0.123	-0.144	-0.136	0.468
Eigenvalues	7.670	5.791	3.064	2.389	1.999	1.535	1.416	1.395	1.152	1.059
% Variance (80.794%)	22.588	17.031	9.012	7.027	5.879	4.514	4.166	4.103	3.389	3.116

[a] In the columns corresponding to each component, the variables associated with the factor are marked by an asterisk referring to loadings higher than 0.5.

Factor 6 accounted for the practice of aquaculture and factor 7 for the practices of crop rotation on land rented or borrowed. These factors can be interpreted as measures of diversification and intensification. Factor 8 was positively correlated with the use of herbicides and on-farm family members, but negatively correlated with the age of the farmers and off-farm activities. This correlation means that large households headed by young full-time men farmers are likely to use herbicides. Factor 9 was related to variables accounting for the level of intensification with the use of insecticides and irrigation equipment for vegetables production by tenant farm households. Factor 10 (3% of the variance) showed a negative correlation between land tenure and production and sale of rice, as non-tenant farmers tend not to cultivate rice, but rather vegetables at a very low level of intensification.

These ten factors of the PCA formed the basis of cluster analysis using an AHC algorithm that grouped farms into five clusters (**Figure 1**), each with its specific production system attributes. Descriptions of the five farm types (FT), aggregated over the three villages, are provided in **Table 4**.

The FT1 comprised 20% of the surveyed farm households. This cluster is predominantly composed of farmers with off-farm employments cultivating small fields in the developed (part of the) lowlands (mean area: 148 m²). These farmers did not possess fields in the undeveloped lowlands. Most of these farmers were young women and men without any level of education and with limited contact with extension services. These households also had a relatively small number of active members in agriculture. Resource limitations oriented those farmers to off-farm activities. Women were mostly engaged in processing agricultural products, craftwork, and trading, while most of the young men were engaged in selling fuel on the black market and distilling palm wine into popular local liquor known as *sodabi*, and motorcycle taxi transport in the nearby cities. The major agricultural-related income source for this type of farmers was the retail of vegetables (57%).

The FT2 comprised 27% of the surveyed farm households. Farms of FT2 were characterized by relatively large fields (average of 1.5 ha) in the undeveloped (parts of the) lowlands and relatively small fields (200 m^2) in the developed lowlands. The farmers were predominantly uneducated elder women. Their households comprised a relatively large number of active members in agriculture. The major income source for these farmers was the retail of rice (57%) and vegetables (70%).

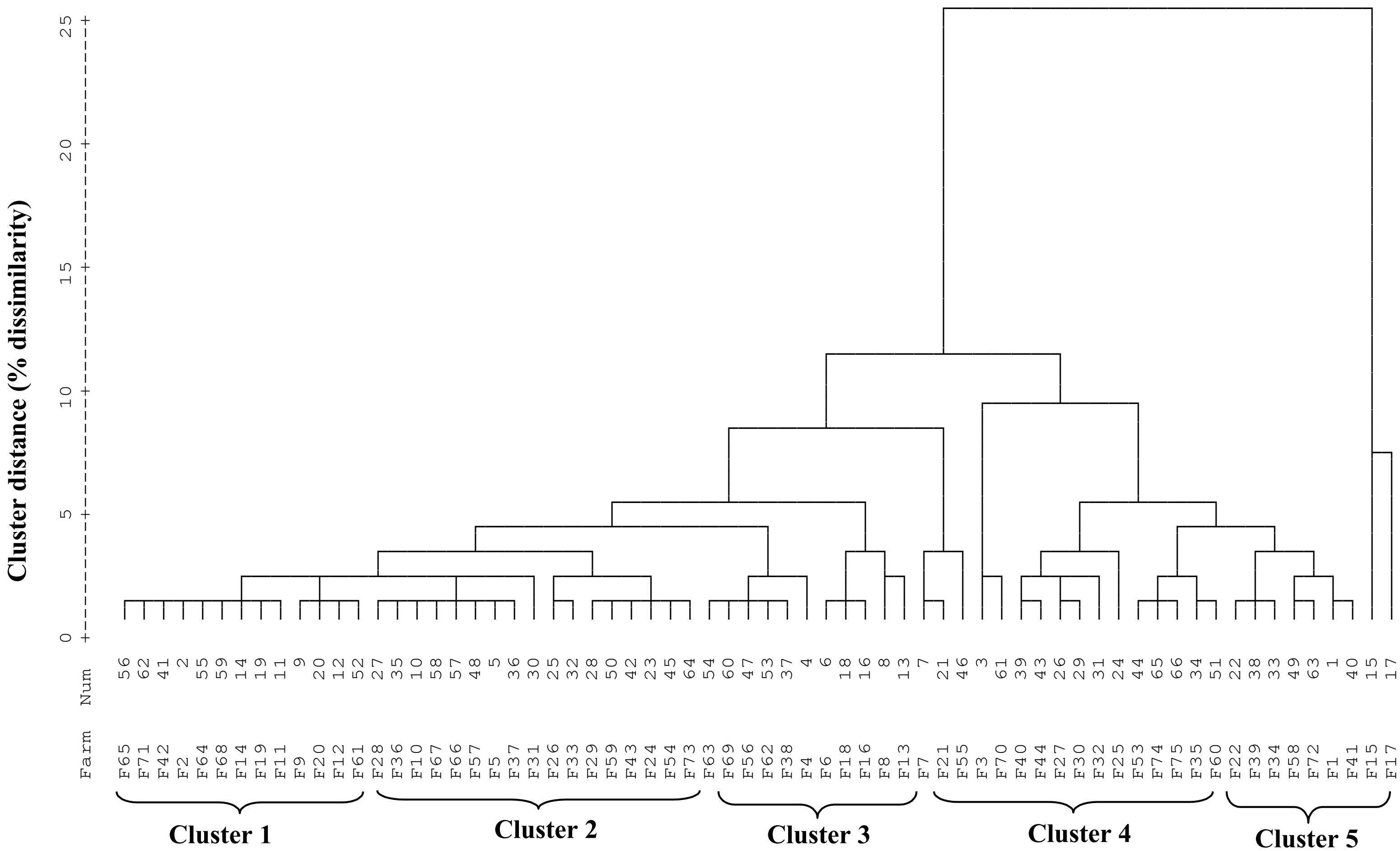

Figure 1. Dendrogram with five possible clusters using Ward's Method and Squared Euclidian Distance. N.B. Characters on X-axis express the farm households (n = 66). Cluster 1 = Farm type 1, Cluster 2 = Farm type 2, Cluster 3 = Farm type 3, Cluster 4 = Farm type 4, Cluster 5 = Farm type 5.

Table 4. Description of major farm types in the proximity of the villages of Agbedranfo, Vovokame and Houinga, South-West Benin.

Variable	Farm type				
	Farm type 1 (20%)	Farm type 2 (27%)	Farm type 3 (17%)	Farm type 4 (23%)	Farm type 5 (13%)
Farm family characteristics					
Gender (%)	Women (92.9%)	Women (86.2%)	Men (80%)	Men (83.3%)	Women (87.5%)
Age of the farmer (year)	33.4±10.9[1]	45.9±14.9	41.6±6.9	43.3±9.9	43.4±12.2
Education level of farmer (%)	None (64.3%)	None (94.4%)	Primary (50%)	None (56.2%)	None (75%)
Contact with extension services (year)	2.1±2.2	2.8±4.1	12.0±6.6	3.8±1.8	2.4±1.2
Total household members (n)	5.2±1.5	6.8±2.5	8.9±4.8	6.7±2.3	5.8±2.0
Off-farm employment					
Off-farm occupation (%)	63	38	30	33	43
Land tenure					
Inheritance/ownership (ha)	-	0.10±0.06	0.69±0.07	0.26±0.02	0.14±0.05
Renting/borrowing (ha)	-	-	0.79±0.38	0.02	0.23±0.02
Farm size					
Developed lowland (m2)	148.1±28.1	200±133	288.9±105.4	611.2±462.6	325±103.5
Undeveloped lowland (ha)	-	1.5±1.2	0.6±0.3	1.3±0.8	0.4±0.2
Labor availability					
On-farm member (%)	14.3	27.8	50	25	30
Technical nature of crop management					
Herbicides use (%)	0	44.4	37.5	39	0
Insecticides use (%)	21.4	5.6	100	12.5	62.5
Fertilizers use (%)	78.6	77.8	100	75	100
Irrigation equipment use (%)	0	11.1	90	25	0
Practice of rotation (%)	66.5	10	100	15.4	100
Capital					
Sale of rice (%)	30.4±23.6	57.3±27.4	19.4±27.1	67.3±17.2	61.9±20
Sale of vegetables (%)	57.3±32.1	69.8±18.8	76±15.7	79±11.8	84.3±16.4
Sale of fish (%)	0	0	25±12.1	0	0
Market access					
Distance to major urban areas (km)	2±0.75	7±2.45	15±9.55	7±3.65	5±1.46

[1] ± standard error of the mean

The FT3 comprised 17% of the surveyed farm households. This cluster was composed of full-time farmers with a relatively high level of resource endowment and a relatively strong capacity for intensification and diversification in agricultural activities including aquaculture (fish farming in ponds). This cluster was dominated by relatively young men that benefited from primary education and more contacts with extension services. Their households had the largest number of active members and used hired labor. The farm size was relatively small (mean undeveloped lowland: 289 m^2; mean developed lowland: 0.6 ha). On farms of this type, external inputs (mineral fertilizers, insecticides, broad-spectrum and selective herbicides) and machineries (motor pumps and water hoses for irrigation purposes) were used for rice and vegetable cultivation. Capital was mainly from the retail of vegetables (76%) and fish (25%).

The FT4 comprised 23% of the surveyed farm households. This cluster represented full-time farmers with an intermediate level of resource endowment, and a relatively low investment capacity. The farm type was characterized by uneducated relatively elder men with relatively large field sizes in the undeveloped lowland (mean area: 1.33 ha) and relatively small field sizes in the developed lowlands (mean area: 611 m^2). The only advanced technologies used by this category of farmers were broad-spectrum and selective herbicides. The use of these advanced technologies was mostly limited to rice. The households of these farmers contained a relatively large number of active members. Retail of rice (67%) and vegetables (79%) was their main income source.

The FT5 comprised 13% of surveyed farm households. This cluster was characterized by farmers with a relatively low resource endowment level and average investment capacity. Field sizes were relatively small (325 m^2 for developed lowlands and 4000 m^2 for undeveloped lowlands). The majority of these farmers were elder, uneducated women with limited contact with extension services. The use of external inputs, i.e. fertilizers and insecticides, was limited to high-value vegetable production. Households of this farm type had a relatively small number of active members. Labor was either sourced from the family or hired. The retail of vegetables (84%) was the main income source of these farmers.

3.2. Cultivation practices and production systems

Local farmers' cultivation practices and production systems are presented in **Table 1**. Most surveyed farmers cut the fallow vegetation at ground level with a machete and leave the slashed vegetation to dry for about one week before burning. When this first burning is incomplete, farmers pile up the remaining slash for a second burning. Land preparation entails tillage followed by harrowing or breaking soil clods into smaller particles. It is carried out as a weed control and prevention intervention, burying and incorporating unburnt weed residues in the soil. Land preparation does not comprise any bunding or puddling. Some farmers, mainly from Houinga, practice minimum tillage and use the systemic herbicide glyphosate for land preparation. Across sites, for the dry season crops okra (*Abelmoschus esculentus* L.) and maize (*Zea mays* L.), seeds are directly sown in rows without soaking or pre-germinating. Jute mallow (*Corchorus olitorius* L.) is broadcast sown by the farmers. Most farmers plant at densities exceeding those recommended, and only few farmers practice thinning later. Transplanting of rice is usually done in rows with seedlings that were often much older than the recommended 21 days.

At Agbedranfo and Vovokame, rice and vegetable production are supported by well-functioning irrigation infrastructure (artesian wells) in developed lowlands. At Agbedranfo, crop rotation is practiced, with rice during the rainy season along the whole catena and vegetables mainly during the dry season. Jute mallow is cultivated mainly on the hydromorphic slopes and in the valley bottom, while okra is cultivated on the drier fringes of the catena. Fish farming in ponds is also practiced, but only at Agbedranfo, by 8 out of 21 farmers (38%). The main fish species are Nile tilapia (*Oreochromis niloticus*) and catfish (*Clarias gariepinus*). At Vovokame, rice is rotated with maize (sweet corn), with rice grown during the rainy season and maize during the dry season. In the study areas, a sub-optimal temporal and spatial integration of crops (rice-vegetables) was observed. Dry season vegetable production is practiced on the better parts of rice fields and at a much-reduced area. At Houinga, rice production is rain-fed because the irrigation infrastructure is not functional. Here, rice is mainly cultivated as mono crop during the period of flooding from May to January along the catena. During the dry season, vegetable crops — comprising mainly jute mallow and to a lesser extent eggplant, pepper and tomato — are cultivated at a very small scale near the boreholes drilled to collect water. When these water sources dry up during the months of January and February, some plots have to be abandoned.

3.3. Weed management strategies

3.3.1. Weed management strategies in rice

During the rainy season, three different weed management strategies for rice (WMSR) were distinguished in the study area (**Table 5**). WMSR1 consists of slashing of weeds and spot burning, followed by tillage and hand weeding interventions in rice. WMSR2 is mainly based on minimum tillage in large fields of the rain-fed lowland with rice monocropping and the use of systemic broad-spectrum herbicides (most often glyphosate) before rice sowing. WMSR3 is based on tillage and broad-spectrum herbicide application (glyphosate) for field preparation, followed-up by the selective postemergence herbicide 2,4-D, in rice-vegetables systems. The first post-planting weeding in WMSR1 and WMSR2 involved hand hoeing, while in WMSR3, a selective herbicide is used. The second weeding involves hand hoeing, in all three strategies. The third weeding is optional, and only executed by few farmers.

Table 5. Weed management strategies used by farmers in surveyed rice and vegetables fields, during rainy and dry seasons 2010 and 2011.

Cropping season	Crops	Weeding strategy	Land preparation	Sowing/planting	First weeding	Second weeding	Third weeding	Additional weeding	Herbicide uses
Rainy season	Rice	WMSR1	Residue burning + manual tillage	Direct sowing + transplanting in line	Hoeing	Hoeing	May be done	None	May be done
	Rice	WMSR2	Minimal	Transplanting in line	Hoeing	Hoeing	None	None	Broad-spectrum herbicide
	Rice	WMSR3	Residues burning + manual/mechanical tillage +/- broad-spectrum herbicide	Direct sowing + transplanting in line	Hoeing + few selective herbicide	Hoeing	None	None	Selective herbicide occasional broad-spectrum herbicide
Dry season	Jute mallow	WMSV1	Residues burning + manual tillage	Broadcast sowing at high density	Hand pulling	Hand pulling	Hand pulling	Up to 5 weeding	None
	Maize	WMSV2	Residues burning + manual tillage	Line sowing	Hoeing	Hoeing	May be done	None	None
	Okra	WMSV3	Manual tillage + mulching	Line sowing	Hoeing	Hoeing	May be done	None	None

Mean working time excluding breaks for the first weeding is 5 man-hours day^{-1}, resulting in a mean weeded surface area of 600 m^2 per day, while for the second and third weeding, it is 3 man-hours day^{-1} resulting in 300-600 m^2 of weeded area per day.

Most farmers weed their rice crop two times during the season: the first weeding is done within 21 days after sowing (DAS) and the second weeding between 43 and 64 DAS (**Figure 2A** and **B**). A large minority of farmers (39% at Agbedranfo, 21% at Houinga and 11% at Vovokame) carries out this first weeding during the period of 7 to 21 DAS, because they consider this first weeding as essential for obtaining a reasonable yield. A small majority of the farmers (61% at Agbedranfo, 43% at Houinga and 72% at Vovokame) first weeds between 22 and 42 DAS.

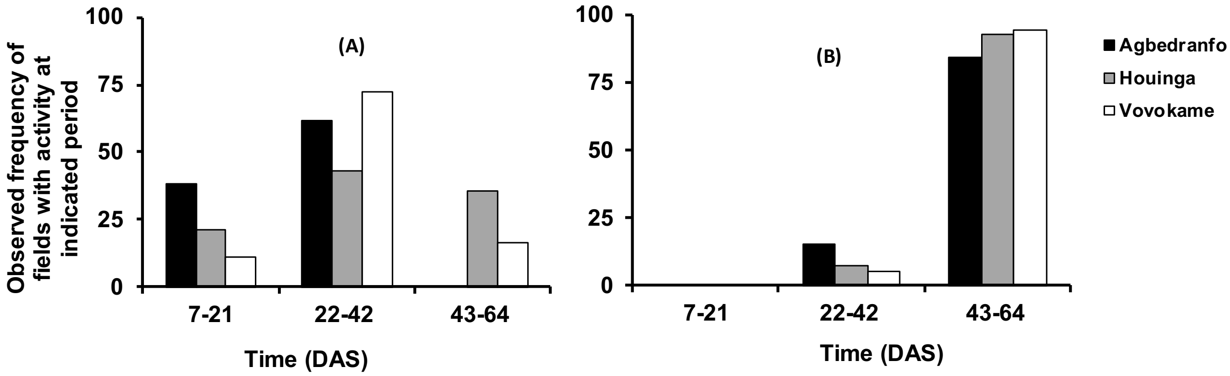

Figure 2. Timing of first weeding (A) (χ^2 = 6.95 P = 0.22) and second weeding (B) (χ^2 = 22.87 P = 0.01), in rice fields during rainy season 2010-2011.

Some farmers in Houinga (36%) and in Vovokame (17%) carry out their first weeding after 42 DAS. For the second weeding, 85% (Agbedranfo), 93% (Houinga) and 94% (Vovokame) of the farmers weed between 43 and 64 DAS. Although farmers are aware that a third weeding favors the development of rice crop, only 5% weed a third time. Hand weeding operations are carried out mostly by women, sometimes complemented by men and children. Farmers practicing minimum tillage (primarily in Houinga) spray the systemic herbicide glyphosate two to three weeks before planting. Supplemental hand weeding is then done to remove weeds that survive the herbicide treatment.

In lowland rice fields, hand weeding is done by all farmers in the three villages (**Table 6**). Hand weeding is mainly done to uproot weeds that have limited root systems (e.g., *Ageratum conyzoides*, *Phyllantus amarus*). Perennial weeds mainly grasses and sedges (e.g., *Imperata cylindrica*, *Cyperus* spp.) are uprooted with hoes and machetes. Among the sub-set of 45 farmers, herbicides are only used in Houinga and Agbedranfo. The sole application of broad-spectrum herbicide is only done by 12 farmers (all from Houinga practicing rice monocropping).

Table 6. Farmer's manual and chemical weed management strategies in rice fields, during rainy season 2010-2011.

Weeding strategies	Agbedranfo n =18	Houinga n = 14	Vovokame n = 13
Hand weeding (n)	18^a	14^a	13^a
Broad-spectrum herbicide (n)	0^b	12^a	0^b
Broad spectrum + selective herbicide (n)	9^a	2^b	0^b
Mean number of sprayings	2.0^a	2.2^a	0^b

^{a,b} Different letters in rows indicate a significant difference (P ≤ 0.05).

The combined application of broad-spectrum (glyphosate) and selective (2,4-D) herbicides is done by nine farmers from Agbedranfo and two from Houinga. Farmers applying herbicides spray on average twice a season and use only one product at a time. The broad-spectrum herbicide is applied to control perennial grasses such as *Imperata cylindrica*. The selective herbicide is used to control annual broadleaved weeds (e.g., *Ageratum conyzoides*, *Eclipta prostrata*, *Ludwigia octovalis* and *Sphenoclea zeylanica*), annual sedges (e.g., *Cyperus difformis* and *Fimbristylis littoralis*) and perennial sedges (e.g., *Cyperus rotundus*).

The use of the different weed management strategies (WMSR1, WMSR2 and WMSR3) is more or less evenly distributed across the upper parts of the catena (from upper fringes to the hydromorphic slopes). WMSR1, relying mostly on hand weeding, was the dominant weed management strategy across the whole catena. WMSR2 and WMSR3, using herbicides, were hardly applied at the valley bottom (**Figure 3**).

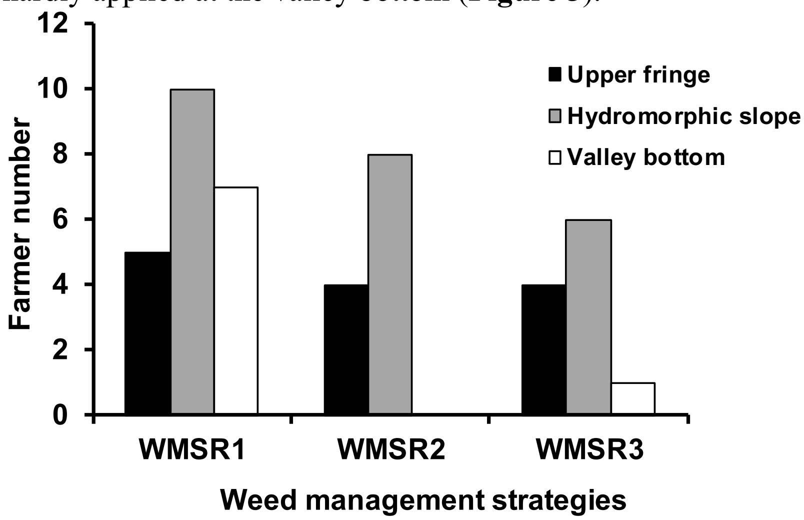

Figure 3. Weed management strategies in lowland rice fields at different catena positions (χ^2 = 6.3 P = 0.18), during rainy season 2010-2011.

3.3.2. Weed management strategies in vegetables

For the main vegetable crops (jute mallow, okra and maize), three weed management strategies were identified (WMSV1, WMSV2, and WMSV3; **Table 5**). In the first two strategies (WMSV1 and WMSV2), the crop establishment follows after burning the residues of the preceding rice crop, and manual tillage with long hoes, while in WMSV3, residues are not burned, but mulched. WMSV1 is strictly practiced in jute mallow plots, and consists of hand weeding up to five times during the season. WMSV2 is practiced in maize, and WMSV3 in okra, and the two strategies mainly consist of two hand-hoeing interventions plus mulching in okra. There is a high consistency among farmers with respect to these crop-specific weed management practices. For the broadcast sown jute mallow with a high plant population density and limited inter-plant space, farmers indicated that it is difficult to enter and to weed the fields without damaging the plants. Hand pulling is the only feasible weed management method here. The first weeding is done within the first three weeks after sowing by all farmers, and every two weeks from then onwards, until the harvest of jute. Maize is first weeded within three weeks after sowing and the second weeding 15 days later. For okra, mulching with rice straw supplemented by straw of grasses (e.g., *Imperata cylindrica*, *Echinochloa* spp.), cut in nearby fallow fields, is practiced followed by a first weeding within the first three weeks after sowing, and a second weeding 25 days later.

3.4. Weed management strategies by farm type

The percentage of farms in each farm type for each of the six weed management strategies (three in rice and three in vegetables) is reported in **Table 7**.

Table 7. Percentage of farmers per weed management strategies in rice and vegetables fields within a farm type during the rainy season 2010-2011.

Weed management strategies	Farm type				
	FT1	FT2	FT3	FT4	FT5
Percentage of farmers practicing					
Weed management in rice					
WMSR1	92.9	16.7	31.2	36.2	80.4
WMSR2	2.1	61.0	12.5	25.0	2.2
WMSR3	5.0	22.3	56.3	38.8	17.4
Weed management in vegetables					
WMSV1	43.4	100.0	60.1	70.0	56.4
WMSV2	56.6	0.0	0.0	0.0	27.8
WMSV3	0.0	0.0	39.9	30.0	15.8

During rice cultivation in the rainy season, the majority of resource-limited farms of FT1 (93%) and FT5 (80%) practiced WMSR1. During the vegetable cultivation period in the dry season, FT1 farmers (57%) practiced predominantly WMSV2, while the majority of farms in FT5 (56%) practiced WMSV1. Farmers on larger undeveloped fields in FT2 most frequently (66%) practiced WMSR2. During the dry season, all farmers in FT2 (100%) practiced WMSV1. Full-time farmers with a high level of resources endowment in FT3 most frequently (56%) practiced WMSR3 during the rainy season. During the dry season with vegetable cultivation, FT3 farmers (40%) were practicing WMSV3, with mulching to control weeds, while 60% practiced WMSV1. Farmers with intermediate level of resources in FT4 followed a rather similar trend as in FT3. For managing weeds in rice, farmers in FT4 practiced almost equally WMSR3 (39%) and WMSR1 (36%). During the dry season, farmers in FT4 more often followed WMSV1 (70%) than WMSV3 (30%).

3.4.1. Rice crop yields and labor allocations per weed management strategies and farm types

Rice yields were highest in WMSR3 (mean: 2235 kg ha^{-1}) and FT3 (2277 kg ha^{-1}) (**Figure 4**). Mean rice yields of WMSR2 (1630 kg ha^{-1}) and FT 2 (1592 kg ha^{-1}) and that of FT4 (1808 kg ha^{-1}), were intermediate. Rice yields were lowest in WMSR1 (1271 kg ha^{-1}) and in FT1 (731 kg ha^{-1}).

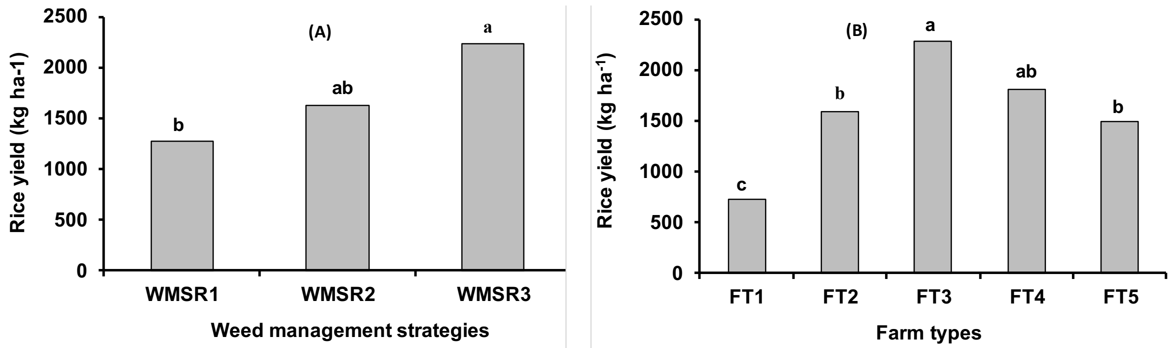

Figure 4. Average rice yields (kg ha^{-1}) obtained by farmers (n= 45) under different weed management practices (A) (P = 0.0036) and by farm types (B) all weed management practices included (P = 0.0019). Values followed by the same letter on vertical bars are not significantly different at the 5% level by LSD test.

The labor for hand weeding in rice was essentially family labor, involving on average 5 to 9 family members. One to two children often participated in weeding operations, but mainly outside school time for 1-2 hours. Hired labor constitutes 25% of the total labor used for hand weeding in rice at Agbedranfo, while no or hardly any hired labor was used in rice at Houinga and at Vovokame. The labor wage for weeding rice was 65 US$/ha. In rice, FT1 and FT5 farmers, who principally weed by hand or hoe, spent the largest amount of time on weeding operations (88 and 86 person-days ha^{-1}, respectively). Farmers of FT2, FT3, and FT4, who applied herbicides, spent less time weeding their rice fields (respectively 65, 29, and 44 person-days ha^{-1}). For FT3 and FT4 farmers, application of herbicides effectively replaced the first weeding time (**Figure 5**).

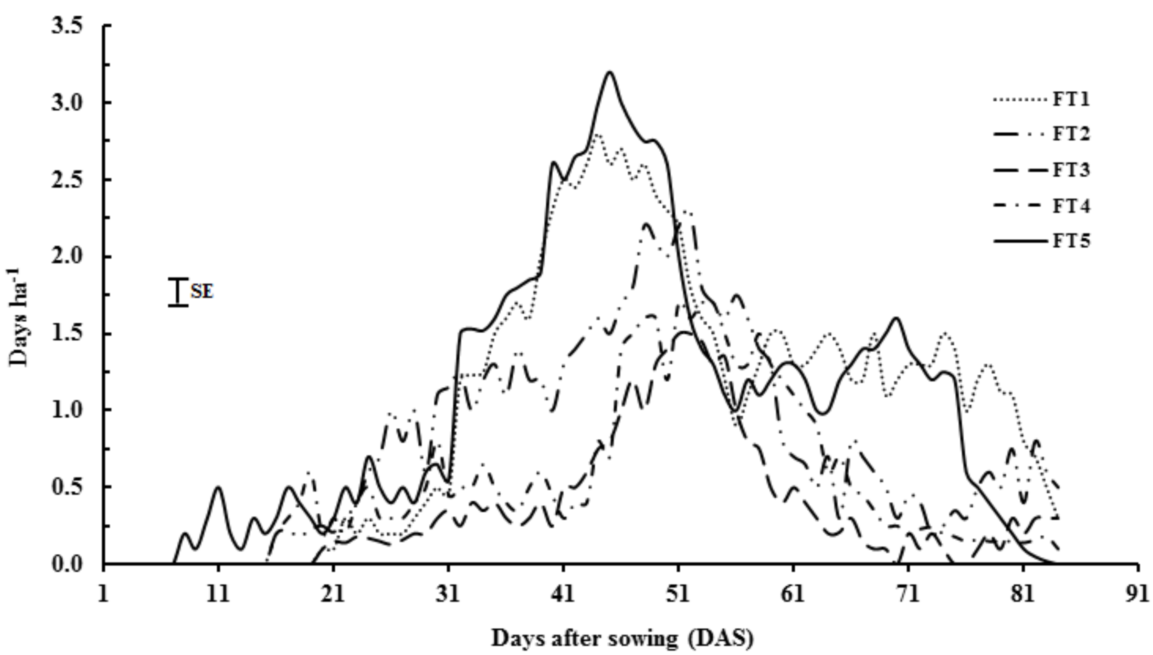

Figure 5. Average time spent weeding rice fields in five farm types in inland valleys of Benin during rainy season 2010-2011. Bar is standard error of the mean.

4. Discussion

4.1. Determination of farmers' weed management strategies based on farm typology

A functional farm typology for inland valleys can assist targeted development and dissemination efforts of production strategies and component technologies (Bidogeza et al. 2009; Diwani et al. 2013; Tittonell et al. 2010, 2014). The present study identified five different farm types in the inland valleys. Farm typology was mainly based on field size, financial resources, labor and gender, all of which have an influence on agricultural productivity and suitability or choices of weed management strategies.

In the study area, rice was primarily weeded during the months of June and July and labor demands were high at that time. Land preparation and planting of other staple crops (e.g., maize), posed another demand on the farmer's limited labor. In this situation, a more important staple crop such as maize was favored leading to the delayed weeding of rice. Dounias et al. (2002) showed that this is a common strategy for smallholder farmers in Africa.

Resources limited smallholder farmers in sub-Sahara Africa are also often risk-aversive (Berkhout et al. 2011), and risk-averse farmers are more inclined to engage in off-farm activities which are perceived as a way to avoid the risk and uncertainty associated with farming (Bidogeza et al. 2009). Low-skilled off-farm activities create major labor shortage within smallholder farmers' households, which may negatively affect weeding. The created labor shortages explain higher weed infestation for part-time farmers found mainly in Farm Type 1 and 5. These farmers had labor shortages early in the cropping season, leading to delayed first weeding, which negatively affected rice yields. Timely weeding of rice is of utmost importance to reduce weed-inflicted yield losses (Johnson et al. 2004; Touré et al. 2011).

FT2 farmers with large fields were in the position to delay their weeding sessions due to the application of the broad-spectrum herbicide glyphosate on undeveloped lowlands before planting. Compared with developed lowlands, these production environments are characterized by larger field sizes and a higher abundance of perennial grass weeds such as *Imperata cylindrica*. The finding that herbicide use increases with farm size, confirms earlier studies, e.g., Beltran et al. (2013). Overall, herbicide application resulted in good rice yields, particularly in minimum tillage systems at Houinga with large fields. However, almost everywhere these chemicals were too expensive for farmers leading to a reduction in the rate of applied herbicide to below-recommended levels. Glyphosate application rate ranged from 0.45 to 0.75 kg active ingredient (a.i.) per ha. The recommended rate ranges from 1.5 to 3.0 kg a.i. per ha with an average of 2.3 kg a.i. per ha (Rodenburg and Johnson 2009). Hence, farmers were applying only 30-50% of the lowest recommended rate. While this reduces the herbicide cost, it increases the time spent in weeding the dry-seeded rice field because of reduced weed control (Rao et al. 2007).

FT3 and FT4 farmers had access to herbicides and labor (family or hired) allowing improved weed management methods leading to higher rice yields. These yields were higher than the estimated average rice yields obtained in rain-fed lowlands across sub-Saharan Africa (Diagne et al. 2013). On vegetables, these farmers could hire labor to cut and carry straws of wild grasses to be used as mulches for better weed management and for soil moisture conservation. Farmers with higher resource endowments (inputs and labor) are more likely to implement and eventually adopt proposed technologies for agricultural intensification (Tittonell et al. 2010).

Herbicide was solely used on rice by FT2, FT3 and FT4; no herbicide was applied to vegetables. Herbicides use in indigenous vegetable production systems in Africa is rare because of the lack of technical advices. Generally, improved agronomic packages provided to farmers are for staple and cash crops and such recommendations often do not exist for indigenous vegetables (Schippers 2000).

In our study, there were no significant differences between weed control strategies at different positions along the catena. The five farm types did not present a diversity of edaphic (soil) and hydrologic conditions; thus, resulting in a uniform distribution of the major weed species. Previously, it was observed that such distribution of major weed species on less contrasted gradients along the catena led farmers not to diversify their weed management practices (Touré et al. 2014). However, in the current study, we did not collect weed data to confirm this trend. Weed management was almost always based on curative interventions and seldom on prevention. The interventions, in turn, were based either on mechanical (hand or hoe) weeding or on a chemical solution. This practice reflects the dominant weed management approaches in rice across Africa (Rodenburg et al. 2019). None of the farmers applied water management (e.g., bunding, drains) as a weed control strategy even in the valley-bottom. Studies by and Becker et al. (2003) and Touré et al. (2009**)** in the inland valleys in Côte d'Ivoire showed that installing field bunds was an effective means to reduce weed infestation levels.

4.2. Identification of entry points for innovations in weed management based on farm typology

System approaches to weed management innovations using farm typology for addressing multiple integration levels can be used to identify heterogeneity at community and regional levels and variability within crop and farm level (Tittonell et al. 2005a; Tittonell et al. 2005b; Rodenburg et al. 2015). Despite the heterogeneous communities, with farmers sharing a common production environment (the inland valley), the study showed that farm types could be differentiated and that the farm types also by-and-large determined the choice and the suitability of weed management strategies. As the weed management strategies varied among farm types, technology options to address these constraints were also expected to differ. Integrated labor-saving and low-cost strategies based on improved cultural practices (e.g., timely hand weeding, bund construction, stale-seed bed, crop rotation and association, use of competitive rice varieties and/or competitive vegetables species, mulching) and rotary weeders may improve weed management for women-headed households with limited resources, such as the cases for FT1, FT2, and FT5. Constraints such as lack of finance, information, and inputs lead farmers to rely on traditional weed control methods such as hand weeding (Rodenburg and Johnson 2009; Tippe et al. 2017; Achandi et al. 2018).

In addition to integrated strategies, capital-based strategies of intensification such as herbicides and motorized weeders may be an option for FT3 and FT4 with better resources endowed full-time farmers who had a good educational basis, and relatively large fields. The decision-making about the use of chemicals was largely influenced by the interactions with extension agents and the availability of products on the local markets. Interaction with well-equipped extension agents is essential for farmers to come to better-targeted weed management strategies (Schut et al. 2015; Rodenburg et al. 2016). Rice farmers across Africa, however, base more frequently the choice of herbicides on what their neighbors use and the availability of products on the markets, rather than on well-informed advices from agricultural extension services (Rodenburg et al. 2019). In other areas, key decision for pesticide selection and use by farmers were based on: (i) performance and effectiveness; (ii) awareness and information; (iii) technical and operational; (iv) environmental criteria; and (v) financial and accessibility criteria (Damalas and Koutroubas 2014; Sharifzadeh et al. 2018). Moreover, it has been previously observed that extension services have a great potential to positively influence farmer decision making. However, this potential is highly dependent on exposure to technologies and access to information (i.e., basic training and access to advice)

(Heong et al. 1998, 2002; Haefele et al. 2002; Becker et al. 2003; Escalada and Heong 2004; Rao et al. 2007; Damalas and Khan 2017).

Minimum tillage can be a solution for farmers with large-size fields to timely prepare their land preparation and sow their crops, but this may result in additional labor requirements for weeding operations (Diwani et al. 2013). Application of glyphosate before sowing of rice can reduce such labor input by 30-60% (Roder et al. 2001). Nevertheless, emerging concerns about the uses of pesticides should be highlighted, as the continuous use of and increasing reliance on such broad-spectrum herbicides, combined with suboptimal application techniques, could lead to the evolution of herbicide tolerant weed ecotypes (Rodenburg and Johnson 2009). It has recently been observed in a continent-wide survey, that herbicides are frequently misused in small-scale rice production systems in Africa (Rodenburg et al. 2019). Indeed, human and environmental welfare concerns and sustainability challenges in pesticide use practices are urgent in rice-based cropping systems in sub-Saharan Africa (Brévault et al. 2014; Machekano et al. 2020).

5. Conclusions

Using survey-data collection with multivariate statistical analyses (PCA and AHC) is a promising approach to generate farm typologies for targeted technology development or dissemination efforts. These tools aid in the identification of important socio-economic characteristics of typical farm households that in turn can be used to determine the suitability of new technologies *vis-à-vis* the available resources.

Farms in the inland valleys of the Mono Couffo regions of Benin are heterogeneous. Results from cluster analysis identified five farm types based on gender, labor availability, farm size, and financial resources. Some types of farms are more inclined or capable to adopt new technologies than others and agricultural extension services should be tailor-made for each specific group.

Farmers are currently focusing mostly on curative weed management practices, and even within this category, a lack of diversity in measures has been observed. Therefore, innovations should focus on preventive measures, such as controlled flooding enabled by bunding, use of more competitive or tolerant rice varieties, off-season weed management to prevent weed seed production, as well as non-chemical labor-saving curative solutions, such as mechanical or motorized weeders. Farm types headed by women farmers, which are often more challenged by inputs and labor shortages will likely benefit most from improved access to information on weed management technologies. Therefore, extension messages, policies, and transfer of technologies and innovations should be more focused on this specific group of women farmers.

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References

Achandi EL, Mujawamariya G, Agboh-Noameshie AR, Gebremariam S, Rahalivavololona N, Rodenburg J. 2018. Women's access to agricultural technologies in rice production and processing hubs: A comparative analysis of Ethiopia, Madagascar and Tanzania. J Rural Stud. 60: 188–189.

Becker M, Johnson DE, Wopereis MCS, Sow A. 2003. Rice yield gaps in irrigated systems along an agro-ecological gradient in West Africa. J Plant Nutr Soil Sci.166: 61–67.

Beltran JC, White B, Burton M, Doole GJ, Pannell DJ. 2013. Determinants of herbicide use in rice production in the Philippines. Agric Econ. 44: 45–55.

Berkhout ED, Schipper RA, van Keulen H, Coulibaly O. 2011. Heterogeneity in farmers' production decisions and its impact on soil nutrient use: results and implications from northern Nigeria. Agric Syst. 166: 63–74.

Bidogeza JC, Berentsen PBM, De Graaff J, Oude Lansink AGJM. 2009. A typology of farm households for the Umutara Province in Rwanda. Food Sec. 1: 321–335.

Blazy JM, Ozier-Lafontaine H, Doré T, Thomas A, Wery J. 2009. A methodological framework that accounts for farm diversity in the prototyping of crop management systems. Application to banana-based systems in Guadeloupe. Agric Syst. 101: 30–41.

Brévault T, Renou A, Vayssières J-F, Amadji G, Assogba-Komlan F, Diallo MD, De Bon H, Diarra K, Hamadoun A, Huat J, Marnotte P, Menozzi P, Prudent P, Rey J-Y, Sall D, Silvie P, Simon S, Sinzogan A, Soti V, Tamo M, Clouvel P. 2014. DIVECOSYS: Bringing together researchers to design ecologically-based pest management for small-scale farming systems in West Africa. Crop Prot. 66: 53–60.

Damalas CA, Khan M. 2017. Pesticide use in vegetable crops in Pakistan: Insights through an ordered probit model. Crop Prot. 99: 59–64.

Damalas CA, Koutroubas SD. 2014. Determinants of farmers' decisions on pesticide use in oriental tobacco: a survey of common practices. Int J Pest Manag. 60: 224–231.

Diagne A, Amovin-Assagba E, Futakuchi K, Wopereis MCS. 2013. Estimation of cultivated area, number of farming households and yield for major rice growing environments in Africa. In: Wopereis MCS, Johnson DE, Ahmadi N, Tollens E, Jalloh A, (editors). Realizing Africa's Rice Promise. Wallingford, UK: CABI; p. 35–45.

Diwani TN, Asch F, Becker M, Mussgnug F. 2013. Characterizing farming systems around Kakamega Forest, Western Kenya, for targeting soil fertility–enhancing technologies. J. Plant Nutr Soil Sci. 176: 585–594.

Dounias I, Aubry C, Capillon A. 2002. Decision-making processes for crop management on African farms Modelling from a case study of cotton in northern Cameroon. Agric Syst. 73: 233–260.

Escalada MM, Heong KL. 2004. A participatory exercise for modifying rice farmers' beliefs and practices in stem borer loss assessment. Crop Prot. 23: 11–17.

Erenstein O, Sumberg J, Oswald A, Levasseur V, Koré H. 2006. What future for integrated rice-vegetable production systems in West African lowlands? Agric Syst. 88: 376–394.

Field A. 2005. Discovering statistics using SPSS: (and sex, drugs and rock 'n' roll). Sage, London.

Giertz S, Steup G, Schönbrodt S. 2012. Use and constraints on the use of inland valley ecosystems in central Benin: results from an inland valley survey. Erkunde 66: 239–253.

Haefele SM, Wopereis MCS, Donovan C. 2002. Farmers' perceptions, practices and performance in a Sahelian irrigated rice scheme. Exp Agric. 38: 197–210.

Heong KL, Escalada MM, Huan NH, Mai V. 1998. Use of communication media in changing rice farmers' pest management in the Mekong Delta, Vietnam. Crop Prot. 17: 413–425.

Heong KL, Escalada MM, Sengsoulivong V, Schiller J. 2002. Insect management beliefs and practices of rice farmers in Laos. Agric Ecosyst Environ. 92: 137–145.

Huat J, Doré T, Aubry C. 2013. Limiting factors for yields of field tomatoes grown by smallholders in tropical regions. Crop Prot. 44: 120–127.

Johansen C, Haque ME, Bell RW, Thierfelder C, Esdaile RJ. 2012. Conservation agriculture for small holder rainfed farming: Opportunities and constraints of new mechanized seeding systems. Field Crops Res. 132: 18–32.

Johnson DE, Wopereis MCS, Mbodj D, Diallo S, Powers S, Haefele SM. 2004. Timing of weed management and yield losses due to weeds in irrigated rice in the Sahel. Field Crops Res. 85: 31–42.

Jordan N, Schut M, Graham S, Barney JN, Childs DZ, Christensen S, Cousens RD, Davis AS, Eizenberg H, Ervin DE, Fernandez-Quintanilla C, Harrison LJ, Harsch MA, Heijting S, Liebman M, Loddo D, Mirsky SB, Riemens M, Neve P, Peltzer DA, Renton M, Williams M, Recasens J, Sønderskov M. 2016. Transdisciplinary weed research: new leverage on challenging weed problems? Weed Res. 56: 345–358.

Khan M, Damalas CA. 2015. Farmers' knowledge about common pests and pesticide safety in conventional cotton production in Pakistan. Crop Prot. 77: 45–51.

Köbrich C, Rehman T, Khan M. 2003. Typification of farming systems for constructing representative farm models: two illustrations of the application of multi-variate analyses in Chile and Pakistan. Agric Syst. 76: 141–157.

Machekano H, Mvumi BM, Nyamukondiwa C. 2020. *Plutella xylostella* (L.): pest status, control practices, perceptions and knowledge on existing and alternative management options in arid small-scale farming environments. Int J Pest Manag. 66: 48–64.

Microsoft. 2013. Microsoft Excel: Statistical analysis. 800 E. 96th Street, Indianaplois, IN 46240. USA.

Ogwuike P, Rodenburg J, Diagne A, Agboh-Noameshie AR, Amovin-Assagba E. 2014. Weed management in upland rice in sub-Saharan Africa: impact on labor and crop productivity. Food Sec. 6: 327–337.

Rao AN, Johnson DE, Sivaprasad B, Ladha JK, Mortimer AM. 2007. Weed management in direct-seeded rice. Adv Agron. 93: 153–255.

Rodenburg J, Johnson DE. 2009. Weed management in rice-based cropping systems in Africa. Adv Agron. 103: 149–218.

Rodenburg J, Le Bourgeois T, Grard P, Carara A, Irakiza R, Makokha DW, Kabanyoro R, Dzomeku I, Chiconela T, Malombe I, Sarra S, Ekeleme F, Mariko M, Andrianaivo AP,

Marnotte P. 2016. Electronic support tools for identification and management of rice weeds in Africa for better-informed agricultural change agents. Cah Agric. 25 15006.
Rodenburg J, Zwart S, Kiepe P, Nartheh L, Dogbe W, Wopereis MCS. 2014. Sustainable rice production in African inland valleys: seizing regional potentials through local approaches. Agric Syst. 123: 1–11.
Rodenburg J, Schut M, Demont M, Klerkx L, Gbèhounou G, Lansink AO, Mourits M, Rotteveel T, Kayeke J, van Ast A, Akanvou L, Cissoko M, Kamanda J, Bastiaans L.2015. Systems approaches to innovation in pest management: reflections and lessons learned from an integrated research program on parasitic weeds in rice, Int J Pest Manag. 61: 329–339.
Rodenburg J, Johnson JM, Dieng I, Senthilkumar K, Vandamme E, Akakpo C, Allarangaye MD, Baggie I, Bakare SO, Bam RK, Bassoro I, Abera BB, Cisse M, Dogbe W, Gbakatchetche H, Jaiteh F, Kajiru GJ, Kalisa A, Kamissoko N, Keita S, Kokou A, Mapiemfu-Lamare D, Lunze FM, Mghase J, Maïga IM, Nanfumba D, Niang A, Rabeson R, Segda Z, Sillo FS, Tanaka A, Saito K. 2019. Status quo of chemical weed control in rice in sub-Saharan Africa. Food Sec. 11: 69–92.
Roder W, Phengchanh S, Maniphone S, Songnhikongsuathor K, Keoboulapha B. 2001. Weed management strategies aimed at reducing labour for upland rice production. In: Roder, W. (Ed.), Slash and Burn Rice Systems in the Hills of Northern Laos PDR: Description, Challenges and Opportunities. International Rice Research Institute, Los Banos, Philippines, pp. 93–102.
Schippers RR. 2000. African indigenous vegetables. An overview of the cultivated species. Chatham, UK: Natural Resources Institute/ACP-EU Technical Centre for Agricultural and Rural Cooperation.
Schut M, Rodenburg J, Klerkx L, Hinnou LC, Kayeke J, Bastiaans L. 2015. Participatory appraisal of institutional and political constraints and opportunities for innovation to address parasitic weeds in rice. Crop Prot. 74: 158–170.
Sharifzadeh MS, Abdollahzadeh G, Damalas CA, Rezaei R. 2018. Farmers' criteria for pesticide selection and use in the pest control process. Agriculture 8: 24.
Somda J, Kamuanga M, Tollens E. 2005. Characteristics and economic viability of milk production in the smallholder farming systems in the Gambia. Agric Syst. 85: 42–58.
SPSS. 2007. SPSS for Windows, Version 16.0. Statistical Package for the Social Sciences Inc., Chicago, Illinois, Chicago (USA).
Tippe D, Rodenburg J, Schut M, van Ast A, Kayeke J, Bastiaans L. 2017. Farmers' knowledge, use and preferences of parasitic weed management strategies in rain-fed rice production systems. Crop Prot. 99: 93–107.
Tittonell P, Vanlauwe B, Leffelaar PA, Rowe EC, Giller KE. 2005a. Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. Agric Ecosyst Environ. 110: 149–165.
Tittonell P, Vanlauwe B, Leffelaar PA, Shepherd KD, Giller KE. 2005b. Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agric Ecosyst Environ. 110: 166–184.
Tittonell P, Muriuki A, Shepherd KD, Mugendi D, Kaizzi KC, Okeyo J, Verchot L, Coe R, Vanlauwe B. 2010. The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa – A typology of smallholder farms. Agric Syst. 103: 83–97.

Tittonell P. 2014. Livelihood strategies, resilience and transformability in African agroecosystems. Agric Syst. 126: 3–14.
Touré A, Becker M, Johnson DE, Koné B, Kossou DK, Kiepe P. 2009. Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Ivory Coast. Field Crops Res. 114: 304–310.
Touré A, Rodenburg J, Saito K, Oikeh S, Futakuchi K, Gumedzoe D, Huat J. 2011. Cultivar and weeding effects on weeds and rice yields in a degraded upland environment of the coastal savanna. Weed Technol. 25: 322–329.
Touré A, Rodenburg J, Marnotte P, Dieng I, Huat J. 2014. Identifying problem weeds of rice-based systems along the inland-valley catena in the southern Guinea Savanna. Weed Biol Manag. 14: 121–132.
Windmeijer PN, Andriesse W. 1993. Inland valleys in West Africa: An agro-ecological characterization of rice-growing environment. ILRI, Wageningen, the Netherlands. 160 p.
Windmeijer PN, Dugué MJ, Jamin JY, Van de Giesen N. 2002. Describing hydrological characteristics for inland valley development. Windmeijer PN, Dugué MJ, Jamin JY, Van de Giesen N, editors. WARDA/ADRAO, Bouake, Cote d'Ivoire.